

Final Report for AOARD Grant FA2386-10-1-4122 "**Integrating Logical and non-Logical Reasoning**"

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**Abstract:** Short summary of most important research results: **Why** (the work was done), **what** (was accomplished), and **so what** (how did this push scientific frontiers or advance the field). This will be used for archival purposes and literature searches.

This project sets out to explore the interaction between logical and non-logical reasoning systems. It is primarily concerned with forging links between two relatively distinct sub-fields within artificial intelligence and to provide both theoretical and practical benefits.

Why: The project's fundamental goal was to explore methods for practical reasoning in the context of robotics. Robotics has seen quite significant advances in the recent past. With increases in miniaturization, computational power, sensor technology and the advent of robotic middleware (e.g., the Robot Operating System (ROS) used in this project and increasingly adopted by the major robotics research groups worldwide) we now have quite sophisticated robotic systems. However, there is a gap in higher-level reasoning and coordination of lower level behaviours. This project bridges that gap by integrating higher level logical reasoning techniques with lower level non-logical techniques.

What: The project has made advances in dealing with erroneous information, approximate reasoning, topological reasoning and languages for practical reasoning systems.

So what: These developments are currently been implemented on a domestic robot (a Segway RMP) operating in a home environment. The project therefore demonstrates practical reasoning in complex environments.

**Introduction:** Include a summary of specific aims of the research and describe the importance of this research and what is the ultimate goal.

Advances in robotics have led to sophisticated sensors and actuators as well as software environments that provide for quite advanced capabilities in particular with regard to mapping, localization, navigation, vision and manipulation. However the high-level coordination of these skills or behaviours has not yet reached the same level of sophistication. The ultimate goal of this project is to investigate practical reasoning by integrating non-logical reasoning methods that have been successfully used in low-level behaviours (e.g., for SLAM, navigation, object recognition, etc.) and logical methods for

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14. ABSTRACT <b>This project sets out to explore the interaction between logical and non-logical reasoning systems. It is primarily concerned with forging links between two relatively distinct sub-fields within artificial intelligence and to provide both theoretical and practical benefits. The project's fundamental goal was to explore methods for practical reasoning in the context of robotics. Robotics has seen quite significant advances in the recent past. With increases in miniaturization, computational power, sensor technology and the advent of robotic middleware (e.g., the Robot Operating System (ROS) used in this project and increasingly adopted by the major robotics research groups worldwide) we now have quite sophisticated robotic systems. However, there is a gap in higher-level reasoning and coordination of lower level behaviours. This project bridges that gap by integrating higher level logical reasoning techniques with lower level non-logical techniques. The project has made advances in dealing with erroneous information, approximate reasoning, topological reasoning and languages for practical reasoning systems. These developments are currently been implemented on a domestic robot (a Segway RMP) operating in a home environment. The project therefore demonstrates practical reasoning in complex environments.</b>					
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high-level coordination of these behaviours. To this end we have developed theoretical solutions for dealing with erroneous information and for approximate reasoning. We have also developed implementations to facilitate topological reasoning and two languages for high level control – one based on a variant of the cognitive robotic programming language GOLOG developed by one of the investigators on this project and another, ALProlog, originally developed for general-game playing by another of the investigators on this project. This has led to the implementation of a ROS framework for controlling a robot in a home environment which provides the experimental setting for the project's developments.

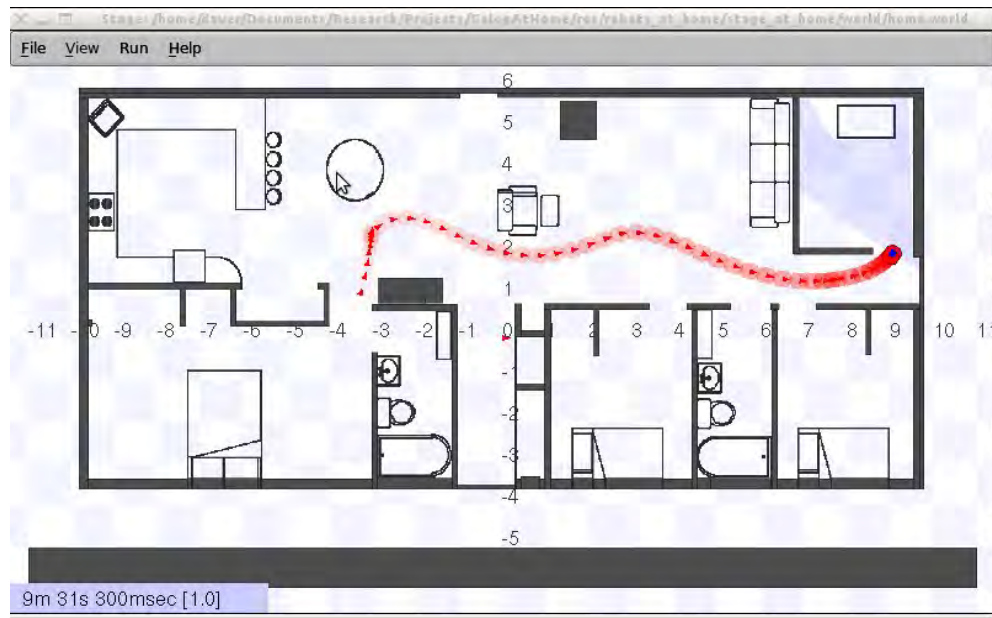
**Experiment:** Description of the experiment(s) performed and the facilities used to perform the work.

A ROS based framework has been developed to provide a platform for experimenting with the integration of logical reasoning and robot control. The platform allows a logical reasoner to send instructions to, and receive feedback from, a ROS controlled robot. Currently, the framework provides a plug-in for the cognitive robot programming language GOLOG (Levesque *et al.* 1997). We use a GOLOG variant developed by one of the investigators on this project (Levesque and Pagnucco 2000) however this can be easily extended to other reasoners and, in particular, we are currently extending the framework to work with the ALPprolog system (Drescher and Thielscher 2011) developed by one of the investigators on this project.

As the framework is based on ROS, we are able to experiment with robot control both in simulation and using real robots in the laboratory. Simple human operator interaction can be achieved using a basic text-based interface while richer more complex interactions can be provided using the multi-modal MICA/FrameScript system (Kadous and Sammut 2004) developed by one of the investigators on this project. FrameScript allows for the development of sophisticated grammars for conversational agents. While we have not yet incorporated a text-to-speech engine for this project, we have done so in the past using the commercial Dragon engine and plan to do this at a later stage.

A basic set of interactions have been implemented in GOLOG to highlight the types of high-level reasoning tasks that would be expected of a domestic robot. For example, the robot can be instructed to go to a room in the house (see Figure 1) as well as to deliver objects to individuals. When the robot is told to “deliver the coke to Bjorn” it first has to reason about the locations of the tagged object “coke” and person “Bjorn”. It then forms and executes the plan to perform this task; namely to move to the kitchen, pick up the coke, move to the living room, where Bjorn is located, and hand the coke to Bjorn. Importantly, the logical operations of the robot is determined at a level of abstraction that reflects the natural intuitions of a human operator. In particular, locations in the house are defined in terms of named regions that reflect the everyday usage of a human operator, for example the different bedrooms, the kitchen, the living, the study, the bathrooms, and the doorways separating these rooms.

Defining the different regions is currently undertaken by a human operator, however, as discussed in the section below on “Topological Reasoning”, we are actively developing semi-automated means for the robot to be able to determine and label regions dynamically while interacting with the operator.



**Figure 1.** Sending the robot from the “master bedroom” to the “study” requires passing through the “dining room”, “living room”, and a number of doorways.



**Figure 2.** Segway RMP platform used for this project.

#### UNSW CSE Robotics Capabilities

The School of Computer Science and Engineering (CSE) at the University of New South Wales (UNSW) is one of the premier Australian computing schools. UNSW is the only Australian university ranked among the top 100 for Computer Science in the Academic Ranking of World Universities 2010 and obtained the most rankings for ICT disciplines in the recent Australian research Council (ARC) Excellence in Research Assessment (ERA) being ranked in five areas (including the area of this research) where other institutions were ranked in at most two areas. UNSW is a partner in the ARC Centre of Excellence for Autonomous Systems (CAS), which includes all investigators on this grant. With over 200 staff and research students, CAS is already the second largest robotics research group in the world with a leading reputation for both fundamental research and the application of this to

industry. In its first eight years, members of CAS produced over 800 research publications, gave 200 plenary/keynote/invited talks at international conferences, won 27 national and international prizes, and graduated 82 PhD students. All investigators on this grant are members of the UNSW node of CAS, which has an outstanding track record in international robotics competitions, including three times RoboCup world champion and three times runner-up in the four-legged league, 2nd place in the recent humanoid Aldebaran Nao-based Standard Platform League competition and 1st place in the technical challenges, and best autonomous robot award in 2009, 2010 and 2011 in the Rescue Robot league.

Autonomous Systems, an area in which this project directly falls, is a priority research area for UNSW. The University has invested more than \$1M in internal grants for building robotics research laboratories and purchasing equipment for research and research training. The UNSW node of CAS has several robot platforms including 5 ActivMedia Pioneers, 9 Aldebaran Nao humanoid robots, 3 urban search and rescue robots, 1 ActivMedia PeopleBot, 1 purpose built human-robot interaction robot, 1 Segway RMP, and several other purpose-built robot platforms that we are expecting to use in the course of our project. They are housed in three laboratories used by PhD students and undergraduate thesis students. In addition to these resources, the UNSW Faculty of Engineering has recently invested \$300K on a 1,152 core computing cluster that is available for large scale simulation and compute-intensive tasks that will be useful for this project.

The investigators have also established contact with some of the foremost research groups in this area throughout Australia and the world. In particular, the Computational Logic Laboratory at Simon Fraser University, the Computational Logic Group at the Technical University of Dresden, the Artificial Intelligence Research Group at the University of Freiburg, the Knowledge-based Systems Group at the Technical University of Aachen and the Knowledge Processing Laboratory at the University of Linköping.

This project has contributed to gaining the expertise within the UNSW CSE Robotics group for establishing the core capabilities necessary to tackle the Robocup@Home challenge. Investigator Thielscher has further contributed much of the funding for the purchase of equipment such as a SegwayRMP robotics platform with laser sensors, microphones and (soon to purchase) robot arms.

**Results and Discussion:** Describe significant experimental and/or theoretical research advances or findings and their significance to the field and what work may be performed in the future as a follow on project. Fellow researchers will be interested to know what impact this research has on your particular field of science.

This project has provided an exploration of the links between logical and non-logical systems as a means of achieving practical reasoning. Many of the main results have been theoretical to cement some of the basic science required to integrate both logical and non-logical forms of reasoning. The practical part of the project has been primarily undertaken within the context of challenges identified as part of the Robocup@Home competition. This competition seeks to focus the attention of the AI research community on easily identifiable problems for which the solution requires a multi-disciplinary approach.

The main outcomes of the project can be summarized as follows:

#### Reasoning with erroneous information

A formal framework establishing how a robot can sensibly respond to situations where it is given erroneous information by a human operator, but can only discover the error part-way through fulfilling a task. The motivation for this research has been to examine the realistic problems with which a robot will be confronted when operating within a home environment.

It further highlights the need for such a robot to develop common-sense notions in order to match the expectations of a human operator. The example scenario examined is based on a challenge from the Robocup@Home 2010 competition. A robot which is given the task of returning with the red cup from the kitchen table arrives in the kitchen to find no red cup but instead notices a blue cup and a red plate on the table, what should it do? The best course of action is to attempt to salvage the situation by relying on its preferences to return with one of the objects available.

Formally, this framework is developed in terms of the Situation Calculus extended with a notion of belief (Shapiro *et al.* 2011) by one of the investigators on this project. Preferences derived from the problem statement and common-sense knowledge are used to derive a plausibility ordering over all initial situations. It is this plausibility ordering that determines how the robot deals with the incorrect information; namely in this case that the robot chooses the blue cup over the red plate when it discovers that there is in fact no red cup.

While the Situation Calculus extended with beliefs provides an expressive formalism for tackling the problem of how an agent can recover when being given incorrect information, it does not provide for an efficient implementation of this formalism. Consequently, we adapt a recent extension of action logics with default reasoning (Baumann *et al.* 2010) developed by one of the investigators on this project and show how the problem can be transformed into a framework which can be efficiently implemented using Answer Set Programming (Gelfond 2008). The basic idea is to treat potentially erroneous information as something that is considered true by default but can be retracted should the agent make observations to the contrary.

The framework developed here provides an expressive and intuitive formalism for describing the problem of how a robot can dynamically respond to being given information that it later finds out to be incorrect. It further shows how this problem can be translated into a formalism that allows for efficient implementation, and therefore provides a path for implementation of this behaviour into existing robotics systems.

This work was presented and well received at the recent AAAI 2011 Workshop on Automated Action Planning for Autonomous Mobile Robots. Based on discussions at the workshop we are currently extending the work to show how our framework can encompass any PDDL description, as PDDL is a popular language used in the planning and robotics domains.

Maurice Pagnucco, David Rajaratnam, Michael Thielscher, and Hannes Strass, How to Plan When Being Deliberately Misled. *AAAI-11 Workshop on Automated Action Planning for Autonomous Mobile Robots (PAMR)*, 2011.

### Approximate Reasoning

Examining aspects of propositional approximate logics. This work goes to the heart of determining logical satisfiability (SAT) within a resource-bounded reasoning context, and is therefore of practical interest in the implementation of reasoning for robotics. This work provides a logical characterisation of the well-known DPLL algorithm (Davis *et al.* 1962) when branching is restricted to a subset of the propositional variables (RDPLL). The work further establishes a link between this class of approximate logics and the notion of a *strong backdoor* of an unsatisfiable problem.

The DPLL algorithm forms the basis of a number of the efficiencies of modern SAT solvers. Despite recent advances in the practical efficiency of logical reasoners, determining propositional satisfiability remains the prototypical intractable problem (unless  $P = NP$ ). This computational intractability remains an important factor constraining the use of logical reasoners in strongly resource-bounded applications such as robotics. Fortunately, this need

to consider the limitations of real agents has led to the examination of different sub-classes of propositional logic for which more computationally bounded behaviours can be determined. In particular the S-3 logics of Cadoli and Schaerf, best summarised in (Cadoli 1995), provide the first logical account of this form of approximate reasoning. These logics are parameterised by a set of propositional formula, the size of which determines the complexity of reasoning for the logic in question.

Unfortunately, the S-3 logics do not provide for a particularly accurate characterisation of the hardness of determining logical satisfiability. For example, a long chain of inferences requiring only the application of unit resolution is well-known to be solvable in polynomial time, yet would be characterised by the S-3 logics as being exponential in the size of the chain of inference. Consequently, in this paper we define an approximate logic for which this sort of inference can be shown to be solvable in polynomial time and therefore more closely characterises the inferences of real SAT solvers.

The family of logics developed in our research is defined in terms of a sub-class of Finger's logics of limited bivalence (Finger 2004) and shown to characterise the behaviour of the RDPLL algorithm. This work therefore opens the way for using more efficient solving techniques in resource-bounded applications such as robotics.

The work has been submitted and accepted at the 2011 Australasian Artificial Intelligence Conference and will be presented at the conference in December of this year.

David Rajaratnam and Maurice Pagnucco, From Approximate Clausal Reasoning to Problem Hardness. *Proceedings of the Twenty-Third Australasian Joint Conference of Artificial Intelligence*, to be published December 2011.

### Topological Reasoning

Identifying the need to draw together the related but distinct areas of Qualitative Spatial Reasoning (QSR) and topological mapping in robotics. QSR is a well established AI sub-discipline looking at symbolic reasoning involving logical spaces. Possibly the most well-known axiomatisation of such a reasoning system is the Region Connection Calculus (RCC-8) (Randell *et al.* 1992). While providing for powerful spatial reasoning capabilities the precise means by which this can be used in robotics research is less certain. The main difficulty is that QSR systems are based on highly abstract notions of logical spaces and consequently do not translate easily to the coordinate systems that are the domain of robotics systems.

While there has been some work on providing a logical basis for map building within a robotics context, for example (Remolina and Kuipers 2004), much of the practical work in robotics is still centred around statistical methods for map construction (such as SLAM) and how this can enable local and global path planning for robots. Map construction and path planning at this level consists of coordinate grids and being able to direct the robot to move to a specific grid coordinate. Unfortunately, this topological view does not provide an appropriate level of abstraction to enable many of the types of abstract reasoning tasks that would be necessary for a domestic robot. For a domestic robot to be of practical use to an operator it would need to be able to reason about regions that correspond closely to the natural divisions that a human operator would assign to those regions. For example, it would need to reason about locations such as rooms in a house, "the kitchen", "the bedroom", "the living room", as well locations defined by sub-regions such as the "the table in the living room".

As part of this project, some preliminary work has been undertaken in this area; for example examining ways of using the occupancy grids built from sensor data to provide operator guided methods for defining abstract regions within a map. Such a system would provide semi-automated techniques that a robot can use to build a coordinate-grounded, but



abstract, model of an environment. The ultimate goal of this component of the research would be to enable a robot to reason about regions within a home environment and the changing relationship between these regions. For example, a robot should be able to reason about moving through the home using high-level information about how rooms are connected, and whether or not doors are open or closed, locked or unlocked.

#### A New Programming Language for Practical Reasoning Systems

Logic programming is a powerful paradigm for programming autonomous agents in dynamic domains, as witnessed by existing languages such as Golog and Flux. We have developed a programming that we called ALPprolog, an expressive, yet efficient, logic programming language for systems that have to reason about incomplete information and sensing actions. Our programming language is intended for the online control of agents, where actions are immediately executed. This starkly contrasts with offline reasoning, where agents may make assumptions to see where these are leading. ALPprolog was developed specifically for the efficient handling of large ground state representations, something that we consider to be practically useful. An implementation of ALPprolog is open source and can be obtained at [alpprolog.sourceforge.net](http://alpprolog.sourceforge.net) (Drescher and Thielscher 2011).

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**List of Publications and Significant Collaborations:** In standard format showing authors, title, journal, issue, pages, and date, please list the following:

- a) papers published in peer-reviewed journals,
- b) papers published in non-peer-reviewed journals or in conference proceedings,

Note: the following are peer-reviewed conferences and workshops.

Maurice Pagnucco, David Rajaratnam, Michael Thielscher, and Hannes Strass, How to Plan When Being Deliberately Misled. *AAAI-11 Workshop on Automated Action Planning for Autonomous Mobile Robots (PAMR)*, 2011.

David Rajaratnam and Maurice Pagnucco, From Approximate Clausal Reasoning to Problem Hardness. *Proceedings of the Twenty-Third Australasian Joint Conference of Artificial Intelligence*, to be published December 2011.

- c) conference presentations,

Maurice Pagnucco, David Rajaratnam, Michael Thielscher, and Hannes Strass, How to Plan When Being Deliberately Misled. *AAAI-11 Workshop on Automated Action Planning for Autonomous Mobile Robots (PAMR)*, 2011.

- d) manuscripts submitted but not yet published, and
- e) manuscripts not yet submitted, and

Maurice Pagnucco, David Rajaratnam, Michael Thielscher, and Hannes Strass, Planning under Erroneous Information, proposed submission for KR-12 with extended version proposed for Artificial Intelligence Journal.

- f) patents that resulted from this work.

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